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Near infrared observations of the truncation of stellar disks

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We present a first study of truncation of the stellar disks of spiral galaxies in the near infrared. Observations of NGC4013, NGC4217, NGC6504 and NGC5981 were made with the CAIN NIR camera on the CST in Tenerife. This wavelength range provides the best description of the phenomenon, not only because extinction effects are minimized, but also because the distribution of the old stellar population is directly obtained. The four galaxies are edge-on and an inversion method was developed to obtain the deprojected profiles. We did not assume any model of the different galactic components. The “truncation curve”, i.e. $T(R) = \mu(R) - \mu_D(R)$, where μ is the actual surface brightness in mag/arcsec² and μ_D the exponential disk surface brightness, has been obtained with unprecedented precision. It is suggested that $T(R)$ is proportional to $(R_t - R)^{-1}$, where R_t is the truncation radius, i.e. the radius beyond which no star is observed. Galaxies: structure, photometry

Introduction

At large radii the stellar density of disks decreases faster than an exponential until reaching a cut-off or truncation radius R_t , where it vanishes. This morphological feature was discovered by van der Kruit (1979) and later studied in more detail by van der Kruit & Searle (1981a, b & 1982). Recently, this phenomenon has been reconsidered by means of samples larger than the seven edge-on galaxies observed by van der Kruit and Searle and by improved observational techniques. Barteldrees & Dettmar (1994), Pohlen, Dettmar & Lütticke (2000), Pohlen et al. (2000) and de Grijs et al. (2001) have provided the basic information about truncations in the optical range for external galaxies. Our Galaxy also presents a truncation, although it is more difficult to observe (Habing 1988; Robin et al. 1992; Ruphy et al. 1996; Freudenreich 1998). Porcel et al. (1997) found that the Milky Way cut-off radius cannot be placed at distances larger than 15 Kpc. Truncations of stellar disks have been reviewed by van der Kruit (2000). Much remains to be done both from theory and observations to understand this phenomenon.

A) Lack of theoretical explanation

The above studies have established the universality of the phenomenon. Most galaxies, if not all, seem to have truncated stellar disks, sensitivity limits alone are unable to explain this feature. This fact emphasizes the theoretical importance of the topic. However, truncations constitute one of the most important challenges in galactic dynamics. Though several hypotheses have been considered, this phenomenon remains completely unexplained.

It was suggested by van der Kruit (2000) that stellar truncation is accompanied by a significant drop in rotation velocity, with NGC4013, NGC891 and NGC5907 being clear examples of this. If this fact is confirmed, and actually takes place in most truncated disks, it would mean that there is a true decrease in the radial distribution of the total density, i.e. the sum of both, the gas and the stellar densities. Theories suggesting that stellar truncation is due to a cut-off of the star formation rate beyond a certain radius should be reconsidered, as in this case the total gas plus star density would not present any discontinuity. The confirmation of a drop in rotation velocity close to the stellar truncation would pose serious difficulties for the most promising hypothesis, maintained by Kennicutt (1989) and others, in which star formation does not proceed when the gas density is lower than a certain threshold value and would reject all theories in which stars do not exist beyond the truncation radius, because they are not formed.

Another argument against the absence of star formation as the cause of stellar truncation is that we do see star formation beyond the truncation radius of the Milky Way. Molecular clouds are often associated with HII regions, IRAS sources, H₂O masers and other objects characterizing the presence of the formation of high mass stars (Mead et al. 1987; Mead et al. 1990; Brand & Wouterloot 1994; Rudolph et al. 1996; Williams & McKee 1997; May et al. 1997; Kobayashi & Tokunaga 2000, and others). A high star formation rate is also observed in other galaxies (Lequeux & Guelin 1996). Wouterloot, Brand & Henkel (1988) and Ferguson et al. (1998) found the important result that the amount of star formation per unit mass of H₂

at $R = 15$ Kpc is equal to that in the solar neighbourhood. The ratio $N(HII)/\sigma(H_2)$ at $R = 15$ Kpc was found to be higher (by a factor 10/7) than in the solar neighbourhood. Though some differences are found between the outer galaxy molecular clouds and the inner ones at $\sim R_\odot$, they have much in common, such as a similar star formation efficiency (Santos et al. 2000) and kinetic temperature (Brand & Wouterloot 1996). The similarities are more noticeable if we compare molecular clouds at $R > R_t$ (where R_t is the truncation radius) and $R < R_t$ but close to R_t . This was done by Brand & Wouterloot (1991, 1994) and Wouterloot et al. (1993) with their sample for $16\text{Kpc} < R < 20$ Kpc and the sample by Mead & Kutner (1988) for $R \sim 13$ Kpc. More information about molecular clouds beyond the solar radius has been provided by Brand & Wouterloot (1995), Wouterloot & Brand (1996) and Wouterloot et al. (1995, 1997). The range of masses and sizes are very similar, and hence the densities should be similar. Cloud formation could be much more inefficient than at smaller R (Brand & Wouterloot 1991). There is indeed, a sharp decrease in H_2 , but not that pronounced in HI gas, which might suggest that the formation of molecular clouds out of HI gas is not as efficient beyond some radius. Small unobservable clouds could have no star forming capacity. However, the sudden step of the rotation curve mentioned by van der Kruit (2000) remains unexplained.

A simplified but reasonable picture would then be: the amount of molecular hydrogen and the number of clouds decrease; but the density within a cloud remains more or less constant; therefore, if there is a minimum H_2 density for star formation it cannot explain the truncation of the stellar disk.

Then the puzzling question is: if there is star formation beyond R_t , where are the stars? There are two possible answers: a) Star formation at these large radii is a recent or transient process, so that stars have not been continuously filling this region. Suppose, for instance, that the outer disk has been formed recently, because the disk forms slowly and its radius increases over time. This hypothesis is considered as a possibility by de Grijs et al. (2000) and van der Kruit (2000) and has some theoretical support from early works by Larson (1976) and Gunn (1982). Given our present uncertainties about disk formation, though, this hypothesis is rather speculative. b) Stars, once born, then migrate away. This could be the case if stars and gas have different dynamical behaviours, being subject to different forces. Newly formed stars could be subject to other forces and migrate from their birth place.

B) Observational problems.

There are two basic features in the surveys and analysis carried out until now which are improved in this work. First, previous observational studies have been made at optical wavelengths, and therefore extinction introduces a severe limitation on the interpretation of the results. Second, the analysis is usually based upon a specific galaxy model with various components of which the space distribution is specified by means of a number of free parameters, which are determined by fitting the observations. However, with this procedure, what is obtained is, in part, what is assumed. Mathematical expressions are still insufficient for many galaxy components.

This fact is specially problematic in the truncation region. It is known that the truncation is not completely sharp, but rather starts as a smooth deviation of the “exponential” disk (i.e. linear when using μ). A truncation curve $T(R)$ would quantify this smooth deviation and can be defined precisely as $T(R) = \mu(R) - \mu_D(R)$ where $\mu(R)$ is the observed surface brightness in mag/arcsec² and $\mu_D(R)$ is the exponential surface brightness extrapolated from the inner disk. We know $T(R_t) = \infty$ in units of mag/arcsec², where R_t is the truncation radius. Previous analysis have mainly considered R_t . Truncations are an interesting object of study, as they could reveal the historical and dynamical properties of a galaxy. However the whole truncation curve, $T(R)$ also contains valuable information. It is therefore worrying that the mathematical expression of $T(R)$ was assumed rather than obtained as a chief objective.

To avoid the extinction deformation of the radial profiles, we have observed in the near infrared, so we are mostly dealing with the old stellar population. We present observations in J and Ks. Extinction in J is more severe than it is in Ks. Therefore, conclusions obtained from our measurements in Ks are more reliable.

Complementary studies in other colours has been addressed by the above cited texts. NIR CCD-like arrays already exist some years, but the recent improvement of two-dimension detectors and, in particular, that of CAIN, has made it possible to reach the truncation region.

To avoid model-dependent results, we have used a numerical inversion method. Binney and Tremaine (1987) describe another analytic method to carry out this deprojection, based on the Abell integral. In our procedure, however, only two assumptions are necessary: axisymmetry and negligible extinction. These two conditions are by no means guaranteed in a disk galaxy but it should be taken into account that axisymmetry

is implicitly assumed in other procedures. Moreover, we have two sides in an edge-on galaxy, which are all very similar in our sample. Even if a non-axisymmetric disk could exhibit two similar sides when a galaxy is seen edge-on, this is rather improbable. Extinction is a problem when using methods based on previous modeling, as dust often has a ring structure rather than following an exponential law and the dust distribution must be risky prescribed. Dealing with NIR observations and observing that our $\mu(z)$ -profiles do not show a secondary minimum produced by a dust lane, inspires confidence in our method. Also, extinction is probably no longer important in the peripheral truncation region.

With this small number of assumptions required, we obtain a non-model-dependent deprojection.

Observations and reduction

The observations were carried out at the 1.5 m CST in the Teide Observatory, Tenerife, with the NIR camera CAIN. This is a common user 2D NIR image camera equipped with a 256^2 NICMOS detector array. Two different plate scales (0.4 and 1.0 arcsec/pixel) are selectable to obtain a narrow or wide field image. We used the wide field optics, which has an effective field of view of 4.3×4.3 arcmin. The objects were selected according to their projected size (D_{25}) to fit within that FOV. The detector control and read-out system was, at the time of the observations, based on dedicated transputer design electronics. In June 1999, the electronics was upgraded to a new design based on San Diego State University controller, adapted in house to the NIR, which provides better noise figures and stability. The transputer controller exhibits several noise correlated patterns which have to be removed during the reduction process by the use of specifically designed software routines.

The observed galaxies were the edge-on galaxies NGC4013, NGC4217, NGC6504 and NGC5981. They were observed in the period 13-19 April 1999, as shown in Table 1. The basic physical parameters of these galaxies are shown in Table 2.

table Observational parameters for the galaxies flushleft tabular—cccccc— Galaxy Day Passband Exp. time Seeing 3σ level

table Physical parameters for the observed galaxies obtained from LEDA database (<http://leda.univ-lyon1.fr>): RA and DEC are the right ascension and declination in 2000, PA is the position angle, d the distance and mabs the absolute B-magnitude flushleft tabular—c—c—c—c—c—c— Galaxy RA Dec Type PA d m_{abs}

In order to correct for the bright and rapidly varying NIR sky background, the telescope was alternatively pointed to six fields in the sky in the order $O_1 S_1 S_2 O_2 O_1 S_3 S_4 O_2$, where the S 's are background and the O 's contain the galaxy. The O_2 field was offset with respect to O_1 , 15" N and 15" E. S_1 was 600" W from O_1 ; S_2 , 900" W; S_3 , 600" E from O_2 ; S_4 , 900" W. Each exposure lasted about 2 minutes.

It was very important to perform good flat fielding, sky subtracting and mosaicing. We used the data reduction package developed by R. Peletier, REDUCE, within IRAF, which is specially suitable for data with a large sky background. We took object images, bias frames at the beginning and/or at the end of the night, dark frames for the two exposure times used (10 and 30 sec) and flatfields to calibrate the sensitivity of the array. We took bright and dark flatfields for each filter with the same integration time; these were then combined and subtracted to remove the effects of dark current, telescope and dome.

The calibration was done by using the UKIRT Faint Standard Stars (Casali & Hawarden 1992) fs18, fs23, fs24, fs27 and fs28. We took 4 blocks of 15 images each, for every filter and for every star, at least three times per night, for different air masses. After calibration the isophote contour maps for the four observed galaxies (see Fig. 1) were obtained by means of IRAF Newcont.

figure [] Contour maps for the observed galaxies: The interval between isophotes is 0.5 magnitudes/arcsec² in all maps. The lower value is 15 magnitudes/arcsec² for NGC5981, NGC4013 in Ks, NGC6504 in Ks and NGC6504 in H; 15.5 mag/arcsec² for NGC6504 in J and NGC4217 in Ks and 16 for NGC4013 in J. East is at bottom and North on right